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SPURV — The First Decade

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⑥ **SPURV — The First Decade,**

⑩ by **H. R. Widditsch**

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TABLE OF CONTENTS

Abstract	1
Introduction	1
General Specifications	2
Pressure Hull, Tailcone and External Appendages	2
Power and Propulsion	5
Fluid Systems	6
Command and Control	6
Azimuth System	8
Depth System	9
Run Programmer	13
Acoustic Tracking and Command	15
Transponder and Decoder	17
Instruments	19
Data System	21
Tape Recorder	23
Launch and Recovery	23
Future Development	24
References	27
Appendix	A1
Depth Options	A1
Correlator	A4

LIST OF FIGURES

	page
1 Self-Propelled Underwater Research Vehicle Resting on Its Dolly	3
2 Self-Propelled Underwater Research Vehicle, Cutaway Drawing	4
3 Fluid Systems Schematic	7
4 Simplified Block Diagram of SPURV Azimuth Control	9
5 SPURV Depth System	11
6 SPURV Run Programmer, Simplified Diagram	14
7 Transponder and Decoder Block Diagram	18
8 Instrument Probes	20
9 Data Tape Format and Content	22
10 Launch and Recovery Operations	25
A1 Depth Step and Ramp Detail	A2
A2 Correlator Block and Partial Timing Diagrams	A3

ABSTRACT

The Self-Propelled Underwater Research Vehicle (SPURV) has been under development at the Applied Physics Laboratory for over ten years and is a reliable and practical research tool. Instrumentation developed for SPURV includes temperature and conductivity probes, a fluorometer for dye tracing experiments and a data recording system. Oceanographic and vehicle performance data are multiplexed and digitized and taped on a special recorder. Digital-computer data reduction provides a run summary printout and system performance check a short time after a run. Data are also telemetered acoustically to the mother ship which carries a transducer array for receiving data and tracking and commanding SPURV. Frequency-shifted and digitally-coded signals are used for the acoustic link. A special code, detected by correlation techniques, is used to enhance data accuracy. SPURV's depth control uses a digital reference which is manipulated to provide incremental, sawtooth or long, slow, ramp-like depth excursions. Course changes and an azimuth program are also available on command. SPURV has been operated on over 100 runs at sea, mainly from Navy AGOR-type ships. Launch and recovery tools and techniques have been steadily refined and can cope with any reasonable sea state.

INTRODUCTION

The vehicle and associated equipment described here have been under development for about ten years and have been in regular use at sea for the last six years. The initial objective was to develop a controllable-trajectory vehicle to acquire data on physical properties of the sea--in particular, temperature and sound velocity. Thus the vehicle obtains data in the horizontal plane similar to that which STD probes obtain in the vertical plane. A depth keeping ability of high accuracy, developed relatively recently, has yielded significant results on ocean microstructure. A 3-element thermistor array on the vehicle's nose was recently placed in service to obtain multiple microstructure data. Another instrument option, a fluorometer, was recently used in dye diffusion and water transport studies.

While the complexity and capability of the instrument and control system have been steadily augmented over the years, reliability has also been improved. Two complete vehicles are now available. On the most recent cruise, the vehicles were run an average of 9 hours per day for 3 successive days, with launches almost always on schedule and without crew exhaustion. Earlier configurations and operational details are described in References 1, 5 and 6.

GENERAL SPECIFICATIONS

The general specifications of SPURV are given in Table I and a photograph of the vehicle is shown in Figure 1. Figure 2 is an artist's drawing showing the location of various vehicle components.

Table I. Vehicle Specifications

Maximum Depth	3600 m	12000 f
Endurance with LR 90 battery	5.5 hr	
Instrument Payload	45 kg	100 lb
Speed	2-2.5 m/sec	4-5 kn
Displacement (in sea water)	430 kg	1060 lb
Net Buoyancy	9.1 kg	+20 lb
Overall Length	3.10 m	10 ft 2 in.
Diameter	0.508 m	20 in.
Dive Rate	1.3 m/sec	
Climb Rate	2.3 m/sec	
Turn Rate	3°/sec	
Acoustic Tracking Range	2000 m	

PRESSURE HULL, TAILCONE AND EXTERNAL APPENDAGES

The pressure hull consists of a central cylinder, 20 inches in outer diameter, and two spherogive end sections. The weight of the pressure hull is 670 pounds, which is about 65% of the net weight. The total pressure hull length is 96.5 inches; the central cylinder is 66 inches long and has two joint ribs and four central ribs, all at 13-inch center-to-center spacings. The center ribs have a rectangular cross-section 1 inch wide by 2 inches deep. Nominal cylinder wall thickness is 1 inch. Each of the three hull sections was machined from a single aluminum alloy (7079-T6) hand forging. (Minimum guaranteed yield for this material is 54,000 psi in the tangential direction.) The end sections are held in place with a one-sixth turn interrupted thread. A face seal O-ring forms the primary joint seal, while a piston seal O-ring acts as a backup and also provides locking action for the end sections. Electrical feed-throughs and pressure ports are located in thickened areas of the end caps or through ribs. No leaks have occurred with the system sealed in this way.

Five pressure hulls have been constructed and pressure tested at depths from 9000 to 9500 feet in the Pacific Ocean. Strain measurements taken during these tests indicate that the hulls should be able to

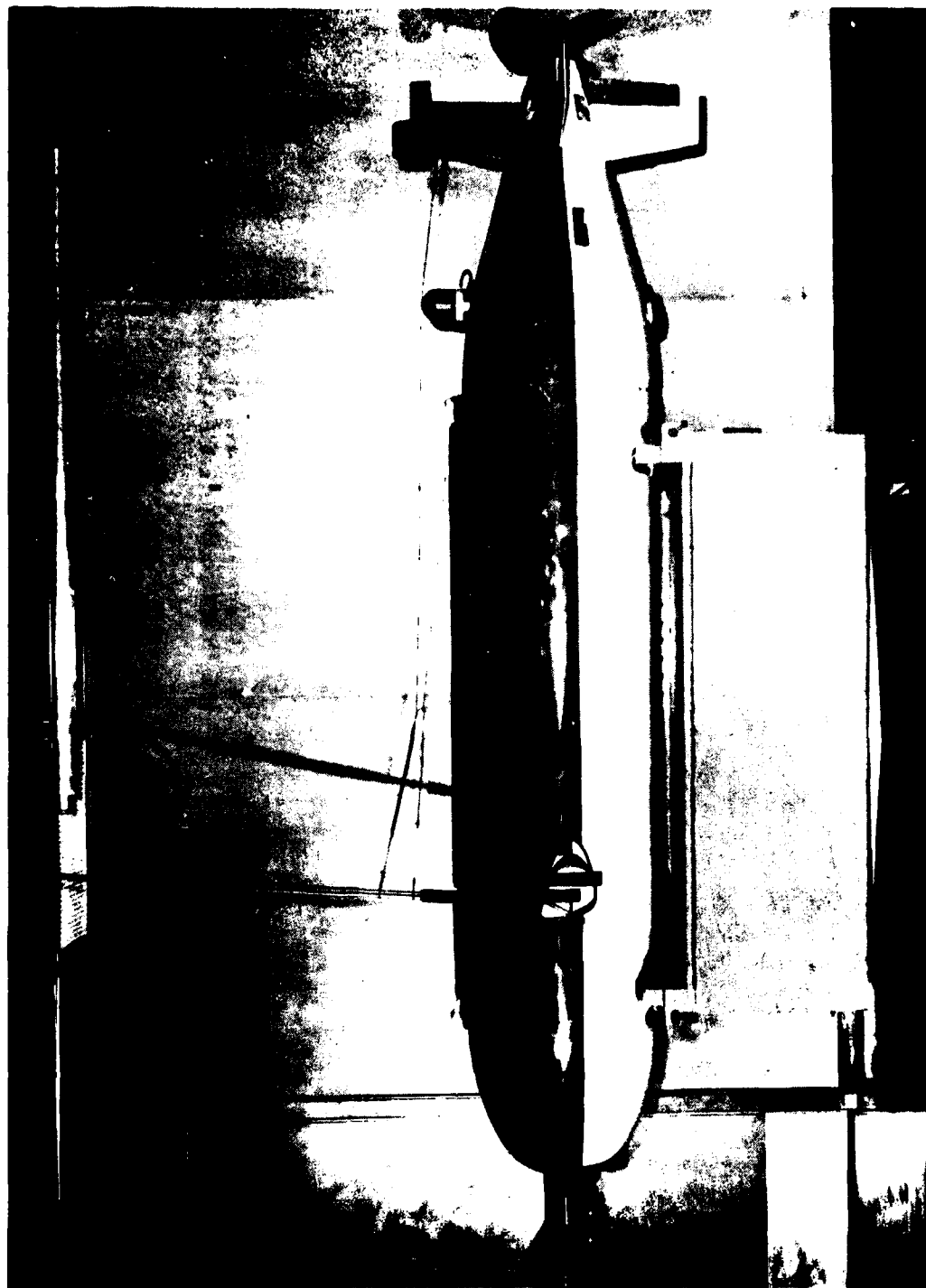


Figure 1. Self-Propelled Underwater Research Vehicle resting on its dolly

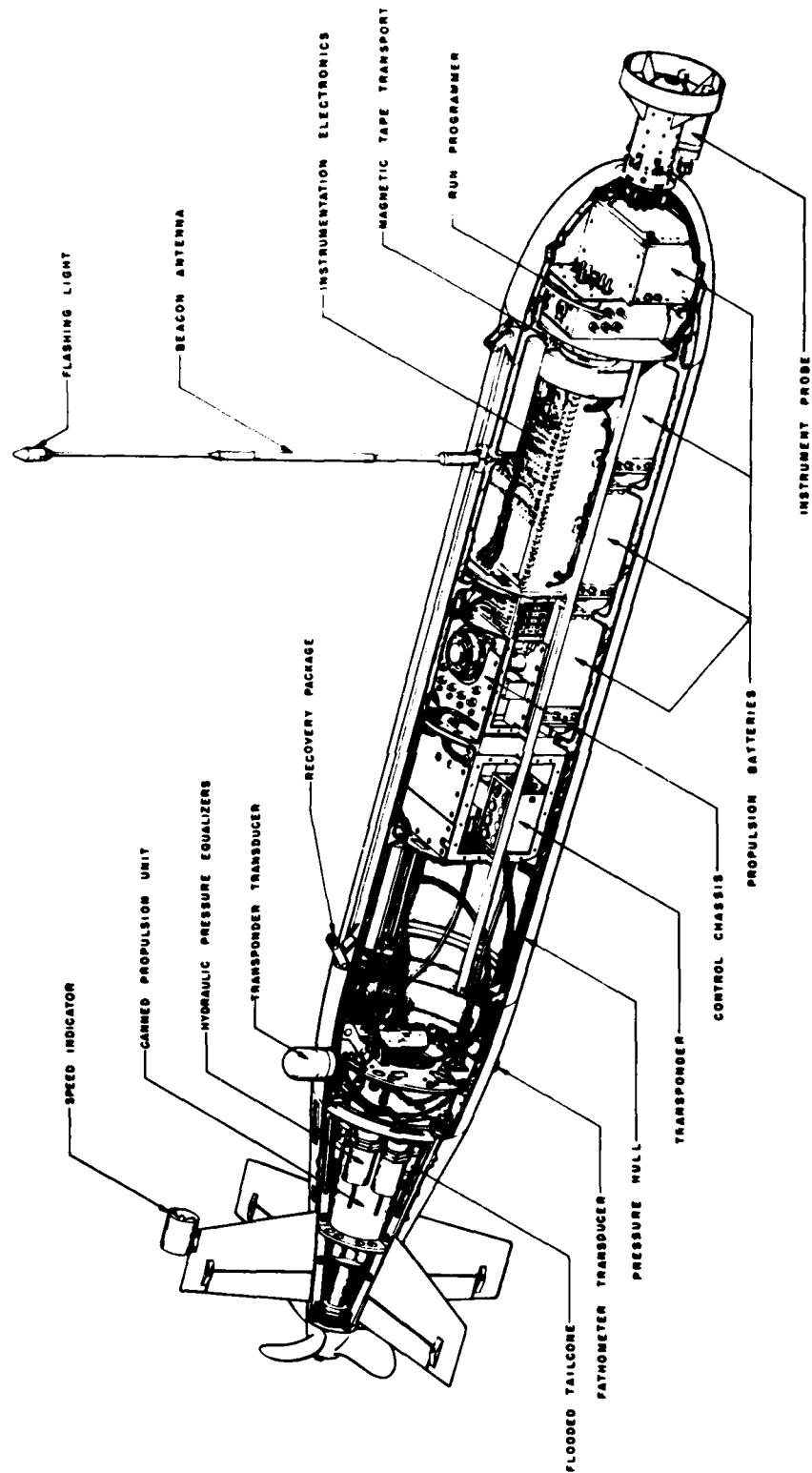


Figure 2. Self-Propelled Underwater Research Vehicle, cutaway drawing

sustain at least 6200 psi, which is equivalent to a water depth of approximately 14,000 feet.

A free-flooded tailcone is attached to the aft section to provide a fairing about the propulsion system and to provide support for the rudder and elevator surfaces. It consists of a 1/16-inch thick spun aluminum skin bonded with epoxy cement to a welded aluminum frame. Located within the tailcone are the pressure equilization cylinders for balancing the pressure between the vehicle's fluid systems and the sea, the solenoids for actuating the elevator and rudder control surfaces, and a block of watertight electrical connectors.

Mounted outside the pressure hull are the handling hardware, the nose instrumentation probe, the tail thermistor probe, a vehicle speed sensor, and the transducers (see Figures 1 and 2). The radio beacon antenna with a flashing light module at its tip is mounted on a very flexible spring so that it will trail close to the hull when the vehicle is under water (see Reference 1). The transponder transducer is located on the top portion of the tail section just aft of the handling hardware. A fathometer transducer is located on the bottom of the aft section of the pressure hull and a vehicle speed indicator is mounted on the vertical stabilizing fin.

POWER AND PROPULSION

The primary power source is the propulsion battery, which consists of 2 sets of 16 silver-zinc cells connected in parallel through diodes to form a 24-volt, 200 ampere-hour supply. The cells are Yardney Electric Co. LR-90 and weight 3.5 pounds. The battery package slides into rails in the vehicle and is electrically lowered in place between the ribs to provide maximum pull-around for roll stability. (The vehicle has no active roll control system.) Under vehicle loads of about 40 amperes total these cells supply almost 130 ampere-hours when new. They average about 100 ampere-hours over the bulk of their service life of 3 to 4 years.

Four solid-state converters provide secondary power. A 60-watt inverter provides ac power at 115 volts, 400 Hz, which is further phase-shifted to give 3 phases. The ac power is used to drive the tape recorder and the run timer; its frequency accuracy is 1%. The dc converters provide +15, +5, +4, -2, -5 and -15 volts for the operational amplifiers and logic circuits used in the data recording and control systems.

The propulsion system includes a dc drive motor, gear reduction unit, drive shaft housing, propeller and motor enclosure. With the exception of the propeller, all are located outside the pressure hull but within the tailcone fairing. The propulsion motor is a 24-volt

shunt motor which has been modified for operation in a fluid bath and is capable of delivering 1 hp at approximately 2000 rpm. The motor is run in a fluid at ambient pressure to prevent the power loss that would occur if a high pressure rotating seal were to be used. Motor efficiency is about 64% under normal propulsion loads of about 1/2 hp. The gear reduction unit is a planetary type with nylon planet gears to minimize noise. The reduction ratio is 6:1; the screw turns at 300 to 330 rpm depending on motor tolerances.

FLUID SYSTEMS

The vehicle has three independent pressurized fluid systems, all components of which are mounted on or inside the tailcone. These systems are illustrated schematically in Figure 3. Each system employs a piston-diaphragm (bellofram) equalizing cylinder as a fluid barrier. Spring pressure on the bellofram piston keeps the fluid pressure almost 2 psi above ambient pressure at all times. Thus rotating seals are subject to only a 2 psi pressure differential. All system seals are continuously working and a leak can be detected by observing the fluid itself or the movement of the piston due to fluid loss. A slow leak during a run would, if it did not exhaust the reserve fluid supply, result only in fluid, not salt water, penetration.

The largest fluid system, the external hydraulic and electrical system, provides conduits for both oil and wiring to the control solenoids, depth cutoff switch, terminal block and transducers. This system includes an oil-filled ring around the periphery of the pressure hull into which electrical conductors are brought after passing through the hull. Hydraulic oil is also piped to the transponder and fathometer transducers along with the electrical wiring. Electrical power to the solenoids is routed through brushes in the solenoid power contact chamber to permit adjustment of the solenoid assembly.

The internal hydraulic system goes through the pressure hull to the pressure transducer (Vibrotron®) and surface cutoff.

The motor system is filled with a petroleum derivative called Stoddard's solution, commonly used as a cleaning fluid. This fluid lubricates adequately and does not interfere with commutation. However, brush wear products contaminate the system and must be scrubbed out at about 50-hour intervals.

COMMAND AND CONTROL

Commands to the vehicle require 12 binary bits in the transmitted acoustic data word, of which 4 are used for the command proper. The

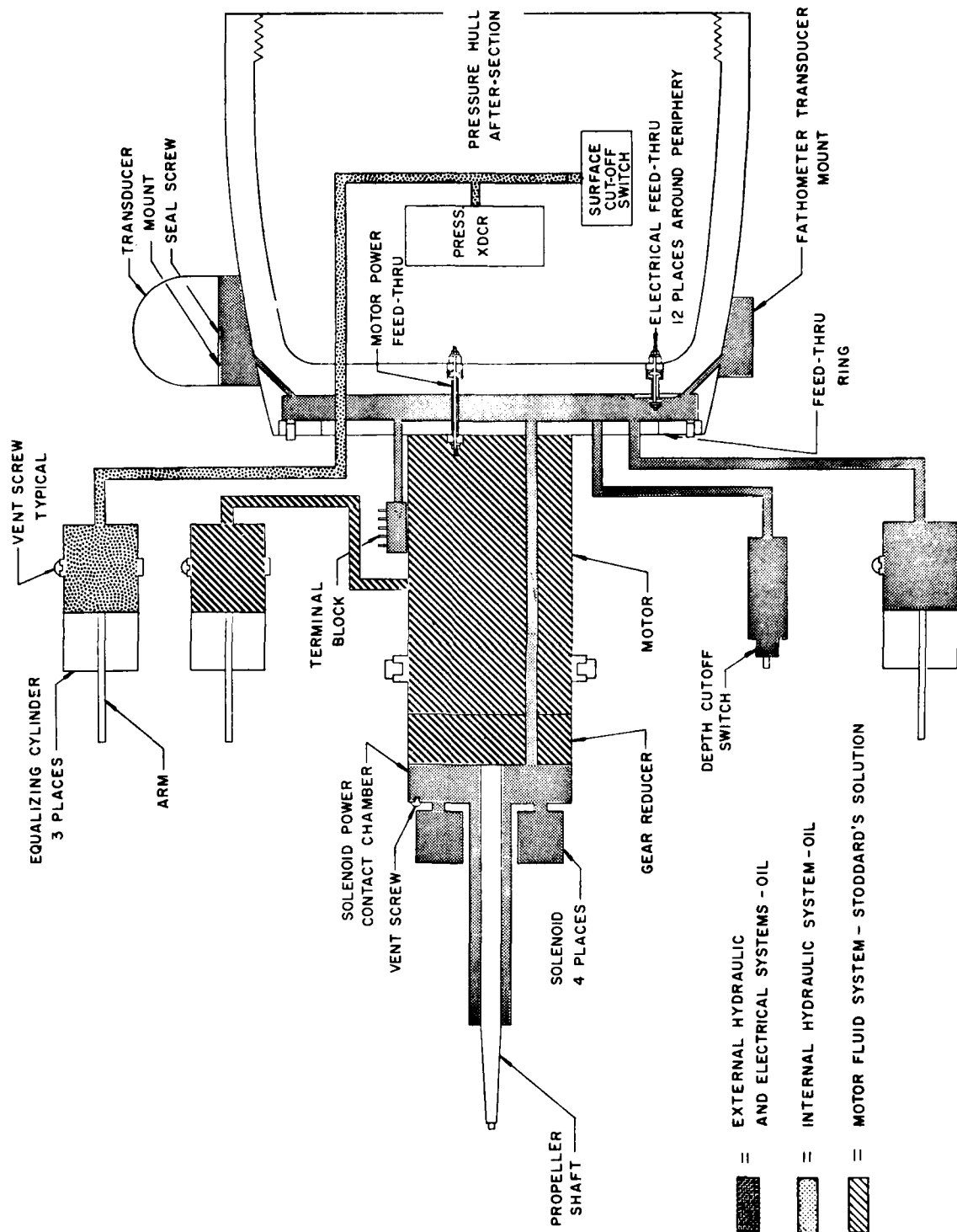


Figure 3. Fluid systems schematic

remaining 8 bits provide incremental depth or course changes referred to as depth or turn steps.

The 4 command bits provide 16 commands which are listed below in decimal order. Some commands have alternative uses which are shown in parentheses.

0 Motor Off-Track only	8 Left turn N steps
1 Surface-Depth 1	9 Azimuth Program ON
2 Depth 2	10 Azimuth Program OFF
3 Depth 3	11 Depth Search ON
4 Depth 4	12 Depth Search OFF
5 Climb N steps (Start Climb Ramp)	13 Hold Ramp (Increase Fluorom. Sens.)
6 Dive N steps (Start Dive Ramp)	14 Reset Ramp (Decrease Fluorom. Sens.)
7 Right turn N steps	15 Spare

The 8 command step bits can provide up to 256 turn or depth steps every 10 seconds, somewhat more than the vehicle can follow. The command options available are, briefly, any one of 3 pre-selected depths from which incremental changes can be made, course changes relative to the initial gyro-retained course, and three programs: a long ramp-like depth change, a sawtooth-like depth search, and an azimuth program. These are described in greater detail in the following sections. The control system is broken down into azimuth, depth and run program subheadings.

AZIMUTH CONTROL SYSTEM

Azimuth reference is established by means of a self-leveling directional gyro. The gyro was obtained from a high quality aircraft autopilot and can be adjusted for a drift rate of less than 1° per hour at most operating latitudes. The azimuth control system is illustrated in Figure 4, which is largely self-explanatory. The gyro is free in azimuth, its only load being a lightweight brush which grounds one of the segments of the split-ring commutator when the course error is large enough.

Prior to launch, the vehicle and ship are pointed in the desired direction and the system is nulled out by entering turn steps until one of the two gaps in the commutator coincides with the brush. Either gap will give a null; however, they yield reciprocal headings. The gaps in the commutator are about 4° wide; hence the vehicle "follows" the gyro to within about 2° . Rudder action is infrequent during straight runs, and power consumption is small. Rudder solenoid activation is recorded on the vehicle's tape recorder.

The 5° turn steps are somewhat large and the system cannot always be nulled out, but a setting close to the null generally suffices. (The 5° step increment was chosen prior to the present multi-step command

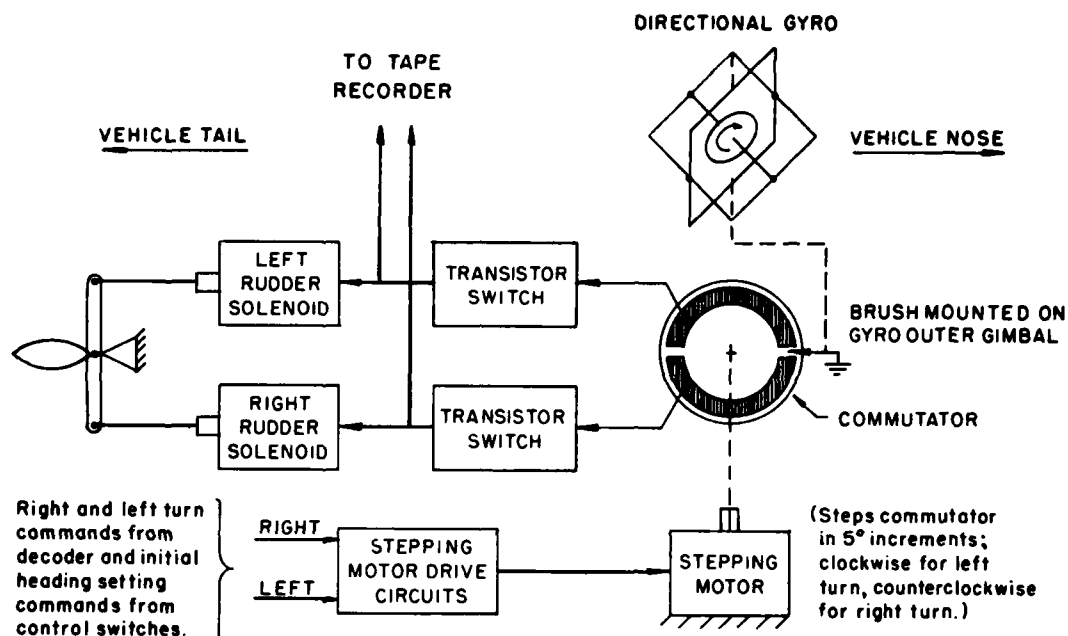


Figure 4. Simplified block diagram of SPURV azimuth control

capability.) A reduction in step size to 1° or 2° could readily be made if there were a requirement for more precise course control.

The azimuth programmer was designed for a specific ocean mapping program in which the vehicle was to map a 2 x 2 mile area with a 0.2 mile grid interval. The grid is a series of perpendicular legs. The programmer turns the vehicle 90° at the end of each leg. The length of each leg is determined by counting pulses from the vehicle's speed detector, which is accurately relatable to distance traveled. Long and short leg lengths are pre-selected and can vary from 0.002 to 2.0 miles. The lower limit is essentially the diameter of the vehicle's turn radius.

DEPTH SYSTEM

In broad outline all depth systems function in a similar manner: a reference voltage proportional to the desired depth is generated, a voltage proportional to the actual depth is provided by a sensor, and the difference between the signals constitutes the error signal which drives

the vehicle in the appropriate direction to reduce the error to zero. The error signal is limited in amplitude and combined with a pitch sensor signal to keep climb and dive angles within bounds.

Figure 5 is a simplified block diagram of the vehicle's depth system showing the major elements and the points at which commands are introduced. The blocks shown in dashed lines in the figure are features which are not an essential part of the depth system but offer additional control options. In the description that follows, the major elements are considered in this order: sensing, control, and reference or command.

In the SPURV system the depth sensor does not provide a voltage directly, but provides a digital number proportional to depth. The most significant 8 bits of the number are compared with a switch-selected digital reference. The resulting "coarse" error signal overrides others until the vehicle is within 30 meters of the desired depth. The lesser 10 bits are converted to an analog voltage and compared against a reference voltage to provide the "fine" error signal. The fine error is nulled when the depth error is less than 0.03 meter.

A new count is generated 12 times a second. If properly stabilized before use by two days of warmup, the Vibrotron will be stable over a 6-hour period within 0.1 meter and its repeatability from day to day will be within 0.5 meter. A more detailed discussion is given in Reference 3.

Referring to Figure 5, depth control starts with the error signal amplifiers and includes all elements which operate from the error signal to control the elevators and, ultimately, the vehicle's body. The body is inherently an element of the depth control system and while its gross characteristics are fixed, different instruments cause changes in drag, speed and force balance. To counteract such effects, the vehicle trim, mainly net buoyancy, and pitch moment are adjusted.

The error signal to the depth control is essentially linear within the fine portion of its range but the control system is nonlinear. That is, the error signal must exceed a threshold level before the elevator is actuated. This causes a so-called deadband in which no control effort is made. The deadband concept can be applied to the electrical signals or to the spatial changes in pitch or depth required to bring about control action. The nonlinearity of the system makes mathematical analysis more difficult but the elevator actuators are much simpler and control power consumption is less than it would be in a linear system. An analysis of the depth control system is given in Reference 7 and a study of the body dynamics is described in Reference 8.

These studies and computer simulations predict that a net buoyancy of 20 pounds and nose-heavy pitch moments of 10 to 20 foot-pounds should result in depth errors of less than 0.1 meter. Further,

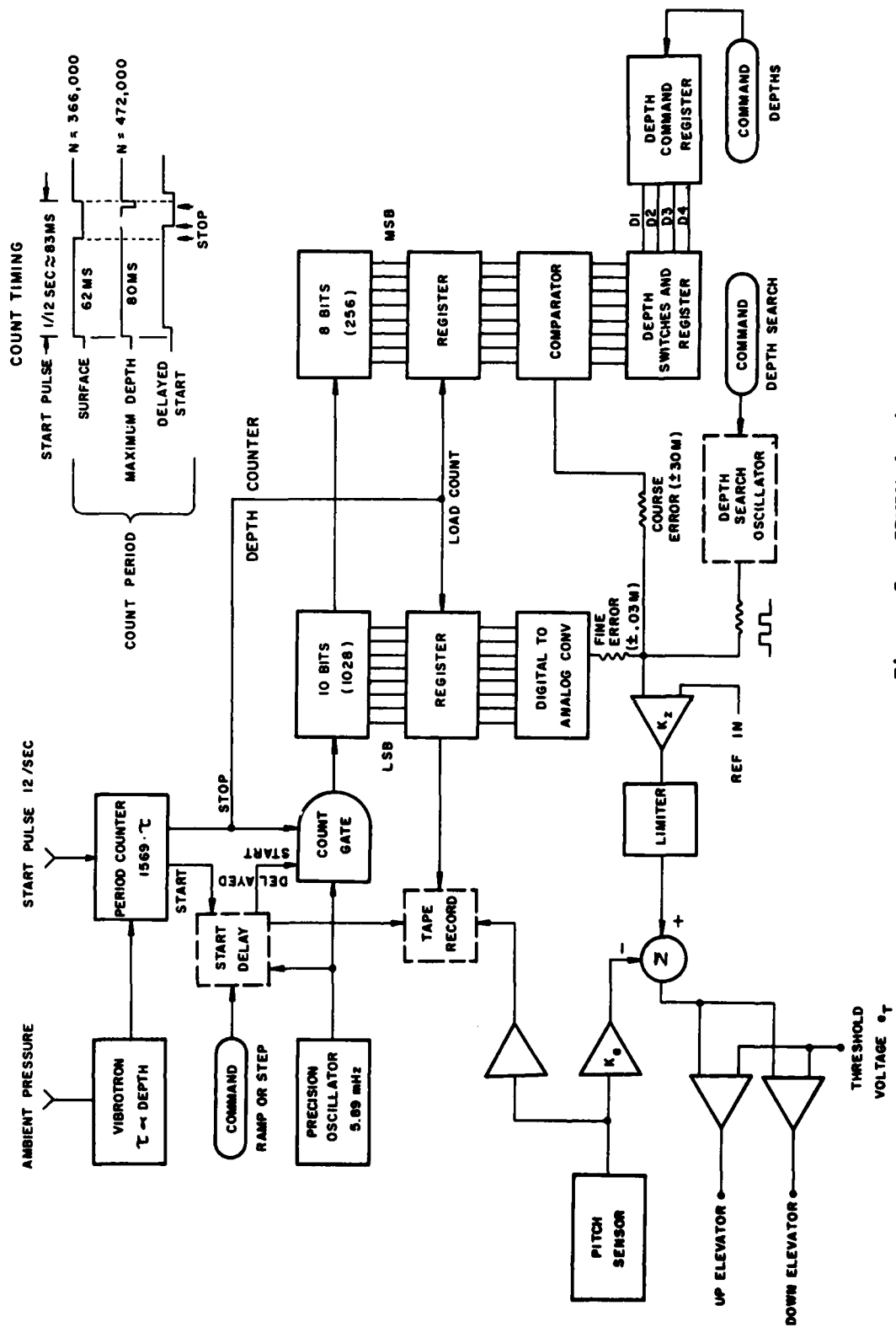


Figure 5. SPURV depth system

the vehicle pitch should oscillate between 1 and 2° with a period of 2 seconds. These values agree well with the actual vehicle performance. The system is very tolerant and has worked over a wide range of conditions.

As new configurations are used, the trim is varied until a more or less optimum arrangement is found. Trim is readily adjusted by positioning lead weights which are mounted on the side of the battery package. The same weights provide pull-around in roll to oppose the roll torque which is generated in reaction to the vehicle's screw. Buoyancy is generally held to 15 to 20 pounds and is trimmed by adding weights at the vehicle's center of gravity.

The basic depth reference consists of three banks of single-pole switches which generate 8-bit digital words defining the three preset operating depths. The command stored in the depth command register determines which set of switches controls the depth register. A fourth depth option is wired for zero depth, i.e. surface. The resolution of the reference is 1024 bits, or about 30 meters. Two additional switches not shown in the figure control two bits of the 10-bit word and give additional resolution down to 8 meters. More resolution can be obtained using the depth step commands described below.

The depth step, depth ramp and depth search command options are represented by a dotted block in Figure 5. These modes operate by changing the output of the depth sensor. The count start is delayed, which shortens the counting period; thus the count is lower than normal and the vehicle dives to raise the count and make it equal to the reference count. The delay is accurately clocked by the precision oscillator and is introduced in steps, each step being 2 or more bits.

The depth step mode starts with a fixed delay of 128 steps, which can be raised to 256 or lowered to zero by using one or several depth step commands. By varying the number of bits per step, the control range can be extended from 8 meters to 230 meters above and below the starting depth.

In the depth ramp mode the steps are accumulated at a constant rate of one per second after the ramp start command is given. The one-second rate is fast enough, compared to the vehicle's response time, so that a smooth motion results. The ramp counter can accumulate up to 4096 steps; thus the program can run slightly over one hour. The ramp must start with a dive but it may be reversed or reset at any point. The depth excursion can be as small as 250 meters or as large as the entire operating range. Block diagrams and a more thorough discussion of these subsystems are given in the appendix.

The depth search mode provides a roughly sawtooth-shaped depth pattern on command. The pattern is accomplished by alternately

changing the depth step delay by a predetermined number of steps above and below 128. A null circuit senses when SPURV is near the top or the bottom of the sawtooth, and reverses the depth step offset with respect to the 128-count starting point. Thus we have a closed loop system which will execute the desired amplitude search pattern at the fastest possible rate. The depth search feature has been used extensively in the study of dye diffusion in the deep ocean.

The parameters of the depth system that are recorded by the vehicle's tape recorder are also identified in Figure 5. Normally only the count in the fine portion of the sensor is recorded. As the vehicle descends the counter repeatedly slowly sweeps through its range; hence total depth can be determined by counting the number of sweeps. It should be noted, however, that when depth steps or the depth ramp are in use the count is no longer exactly proportional to depth since bits are dropped due to the start delay. Therefore the start delay is recorded and used to obtain the exact depth. The pitch sensor output is also recorded. The signal processing and recording methods are described later in the section on the data recording system.

RUN PROGRAMMER

The run programmer includes the run timer, which is the main control element during a normal run, and various circuits and devices to cope with abnormal situations. Figure 6 illustrates the relays and switches insofar as they are involved in run programming--for simplicity, most of the power control functions are not shown.

The run timer is driven with 400 Hz power through the timer relay. The timer's basic period is 6 hours, of which 5 hours and 50 minutes can be used. The timer contains 3 cams from which 2 run periods are obtained: a launch and depth run period and a surface return period. The depth run period is set to the hour and minute up to slightly more than 5 hours. The surface return period can be set from 0 to 45 minutes but the sum of the two periods cannot exceed the 5 hour, 50 minute limit. The depth run ends when both the hour and minute cams reach zero, releasing the run length relay which signals for an up elevator. The surface return period is obtained by rotating the shutoff cam relative to the hour cam such that the desired time delay results.

Referring to Figure 6, propulsion motor operation requires closure of the gyro relay and a series of other switches and relays. At launch the gyro relay is held on through the minute cam. After a depth of 15 meters is reached, the surface cutoff switch and the cutoff cam latch the gyro relay until the vehicle returns to the surface.

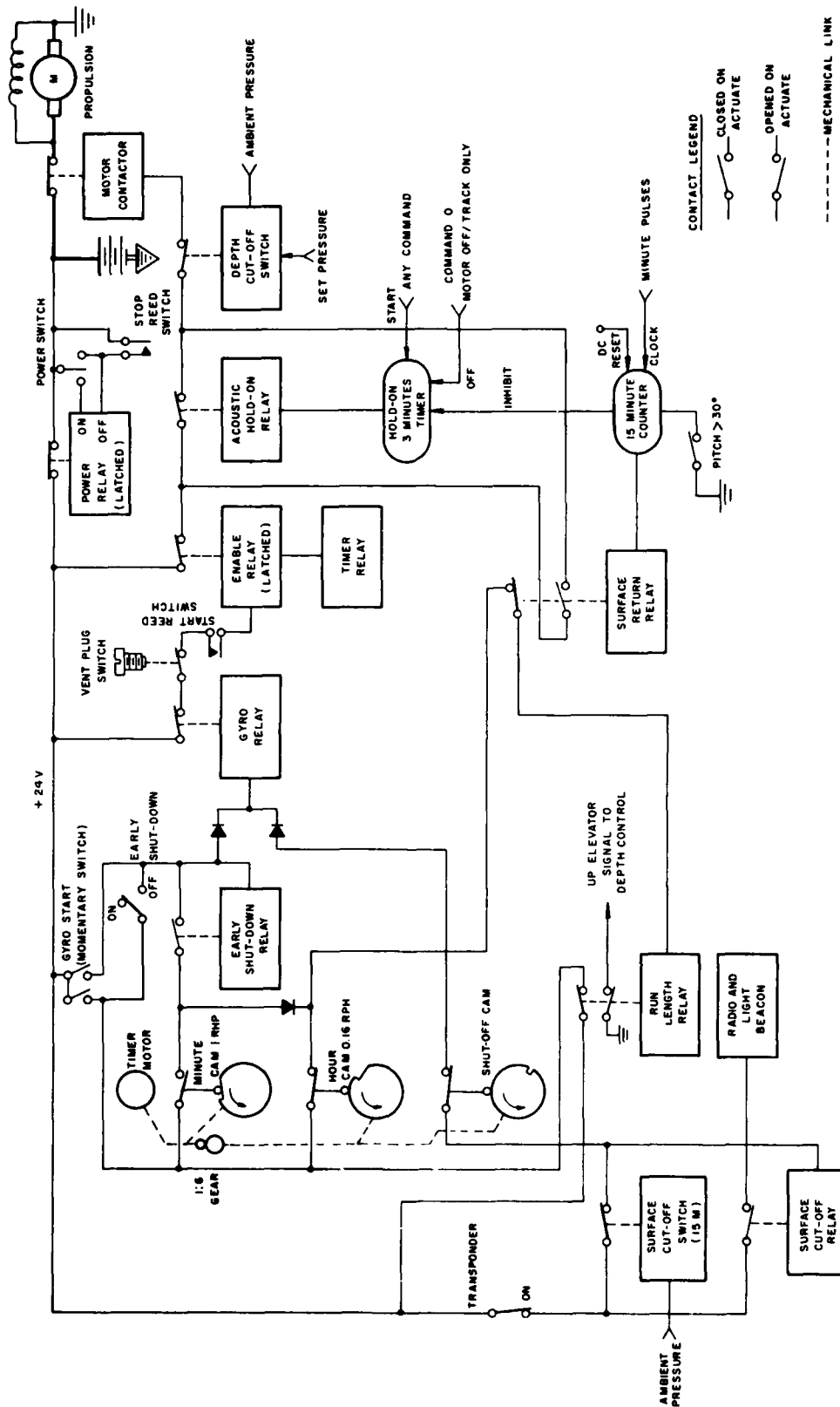


Figure 6. SPURV run programmer, simplified diagram with switches and relays shown in depth run condition.

If the vehicle fails to dive and the early shutdown switch is on, all power except the radio/light beacon is shut down when the minute counter reaches zero. The early shutdown feature is most useful if the minute setting is relatively short, for example 5 to 15 minutes. In any case, the minute setting must be nonzero for the system to latch on. The motor alone can be stopped by commanding the vehicle to surface and turning off the tracking system. Since vehicle recovery is more hazardous when only the motor is stopped, a reed stop switch is provided which can be operated through the hull with a magnet.

Included in the chain of control over the motor is the vent plug (which must be driven home), the magnetically operated start switch which is used to start the motor (and timer) at launch, the acoustic hold-on relay and the preset depth cutoff switch. The acoustic hold-on timer must receive a tracking pulse at least once every 3 minutes. Alternatively, the motor can be stopped at any time without interrupting tracking by sending command 0. The depth cutoff stops the motor if the vehicle dives below the preset depth limit, e.g., because of control system failure.

If the acoustic hold relay releases, the 15-minute counter starts. When the count reaches 14 it activates the surface return relay which restarts the motor and signals up elevator. Then if the vehicle climbs normally and reaches 30° up pitch within one minute, as detected by a mercury switch, the return to the surface continues. If the vehicle does not climb normally, the counter releases the surface return relay, stopping the motor, and disables the acoustic hold-on so that the motor can no longer be restarted. If tracking is re-established within the 14-minute period, the run will resume and the counter is reset.

When motor power is lost, the vehicle will float upward at a rate of about 0.33 meter per second at 20-lb positive buoyancy.

ACOUSTIC TRACKING AND COMMAND

Frequency diversity and frequency shift keying (FSK) are used in the tracking system. Transmission to the vehicle is at 20 and 22 kHz and the vehicle replies at 26 and 28.9 kHz. The lower frequency in each case is used for a 0 in the digital word. The frequency diversity prevents crosstalk problems when more than one device is being tracked. Although this system gives good performance with signal-to-noise ratios down to 6 dB, it is susceptible to multipath propagation.

The structures of the transmission and reply are as follows. There are 25 bits in a word, each bit 1 msec in length. The word to the vehicle is coded as follows:

Bit No.																								
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
0	0	0	1	1	0	1	0	1	X	I	I	8	4	2	1	128	64	32	16	8	4	2	1	P
Correlation Code									Identity		Command				Command Steps									

Transmission to Vehicle
0 = 20 kHz 1 = 22 kHz

The first 8 bits are used only for the correlation code which is used to accurately time the data loading. Bits 11 and 12 are identity or address bits which are used to permit selective tracking of up to 4 objects other than the vehicle. (Bit 9 alone serves as an identity code for the vehicle.) The command bits 13 through 24 are binary-coded with the most significant bits sent first. Bit 25 is a parity error-detection bit which is chosen so that there are an even number of 1's in the bits following the correlation code. If the parity of the command as received does not agree with the parity bit the command will not be stored or executed. Although every transmission to the vehicle includes command bits they usually simply reiterate the operating depth (D2, D3, or D4), and are essentially tracking pulses.

The vehicle's reply code is as follows:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
0	0	0	1	1	0	1	0	S	S	I	I	E	E	512	256	128	64	32	16	8	4	2	1	P
Correlation Code								Status		Ident.		Error		Telemetry Data										

Transmission to Ship
0 = 26.0 kHz 1 = 28.9 kHz

The reply code correlation and identity bits are the same as in the incoming transmission but telemetered data bits replace the bulk of the command bits.

The error codes convey the following information:

0,0 Normal
0,1 Redundancy error - last two transmissions not identical
1,0 Parity error
1,1 Busy - step turn or depth command being executed

The redundancy code relates to the fact that two successive identical commands must be received before the command is executed. When a new command is received it is stored and a redundancy code is sent. On the next receipt the command is executed and a normal code is sent. Parity indicates that there was a parity error in the received word. Busy indicates that turn or depth steps are stored in the step counter and no new command will be accepted until the steps have been completed. In practice the operator must monitor the replies to avoid, for example, sending too many turn steps. Of course the lockout feature of the busy circuits helps to avoid this problem. If several kinds of errors occur the reply code will generally be "busy," except that redundancy and parity errors together give a parity error code.

Bits 9 and 10 are used to telemeter critical vehicle operating conditions, including low battery voltage and propulsion motor operation. The remaining code indicates that the tape recorder motor is operating, which also indicates that the 400 Hz power supply is operating.

TRANSPONDER AND DECODER

A simplified block diagram of the transponder and decoder is given in Figure 7. The timing of the system is synchronized by the correlator clock. The correlator samples the incoming data and stores the samples in a rapidly circulating memory. The memory stores a speeded-up replica of the correlation code. The replicas are repeatedly compared to an internally generated correlation code and when a close match is obtained a trip pulse is generated and the subsequent bits 9 to 24 are averaged and clocked into the main register. The correlation trip controls the timing of the clock pulses and the operation of the data averager. A more detailed discussion of the correlator and a block diagram of the system are given in the appendix.

As the incoming word is loaded into the main register the stored word is recirculated through the storage register and the two words are compared bit by bit. That is the redundancy check. At the same time, parity of the incoming word is checked. If both error tests are passed the new word is loaded into storage, decoded and executed. As the incoming word is clocked into the main register it is also loaded into a register in the data recording system. When bit 9, which is always 1, reaches position 16 in the main register the receive period ends and the new command is transferred to the storage register and decoded.

Decoding of the command involves changing it from binary to decimal, then either storing the instruction or sending it to the appropriate circuit. For a step command the step count is loaded into a down counter and the busy condition is set. The steps are cleared at a rate of 1 step per second. When the counter is cleared the busy period ends and new commands can be decoded.

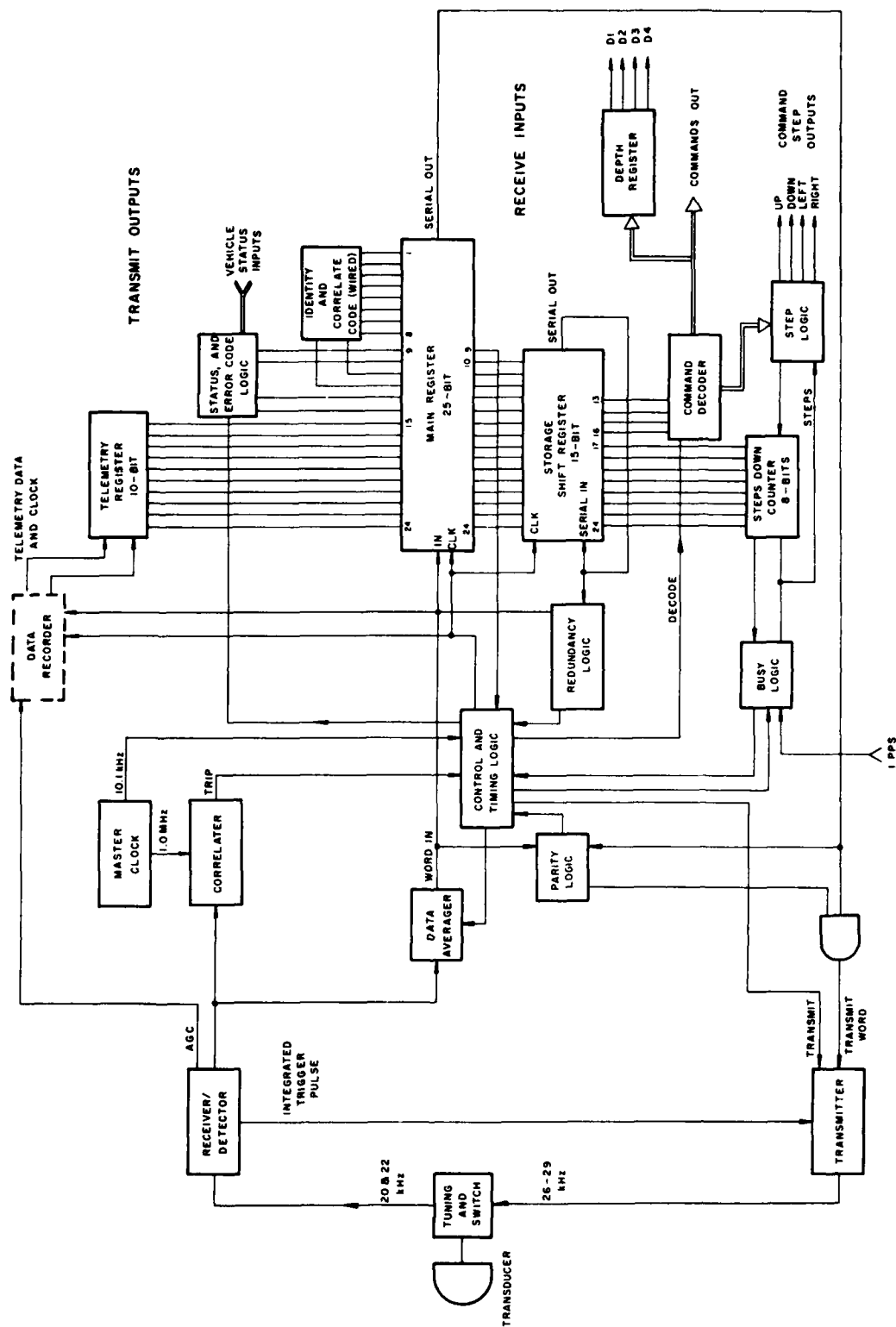


Figure 7. Transponder and decoder block diagram

Two milliseconds after the end of the receive period transmission starts. The telemetry data are loaded into their register asynchronously and transferred to the main register just before transmission. At the same time appropriately coded error bits and the wired identity and correlation bits are loaded. The parity of the word is checked as it is shifted out of the register and the parity bit is added onto the end. The word bits and a transmit level are routed to the transmitter where the FSK signals are generated. As the bits are shifted out one end of the register, 1's are loaded into the other end and when the register contains only 1's the transmit cycle ends. The whole process from correlate trip to completion of transmission takes 42 milliseconds.

In addition to its detected FSK output, the receiver contains a simple integrator which supplies a pulse whenever a 25-msec long input signal is received. This pulse is sent to the transmitter where it will trigger a short reply if the main battery voltage is below 21.0 volts or there is a power failure in the decoder electronics. This feature permits tracking to continue in the event of such problems since the transponder is essentially self-contained.

The AGC level in the receiver is recorded and provides a useful check on operating noise. Since the receiver gain is quite stable AGC is affected mainly by flow noise or abnormal electrical noise.

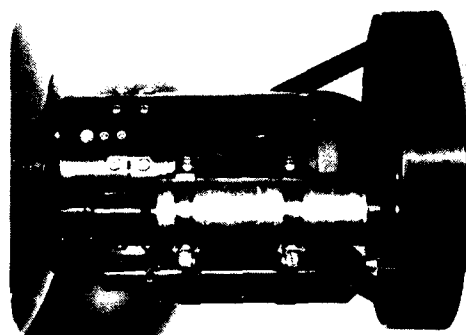
INSTRUMENTS

The standard nose probe package for SPURV for some years included three elements: a velocimeter (sound velocity), a quartz thermometer and a thermistor-controlled Wien bridge oscillator (WBO). The probe is shown in Figure 8a. All of the elements are individually packaged for depths up to 10,000 feet and they all generate frequencies which are measured and recorded in the instrumentation chassis.

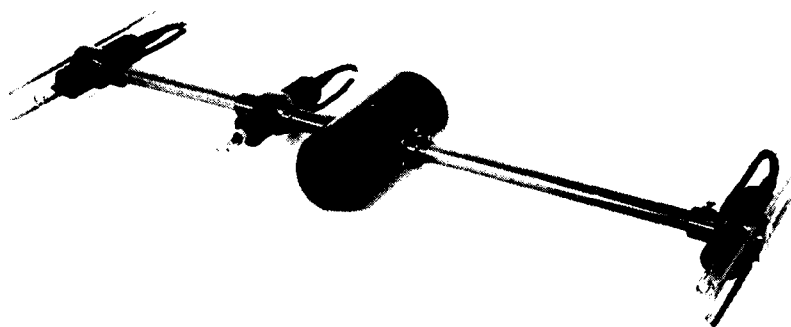
The velocimeter is a sing-around type manufactured by Lockheed and has a resolution of 0.013 meter per second.

The quartz crystal thermometer (Figure 8b) is a relatively slow instrument of high accuracy. The crystal is made by Gulton (Model MET-2) and has a specified accuracy of $\pm 0.01^{\circ}\text{C}$ over a 6-month period. The resolution of the thermometer is 0.00056°C .

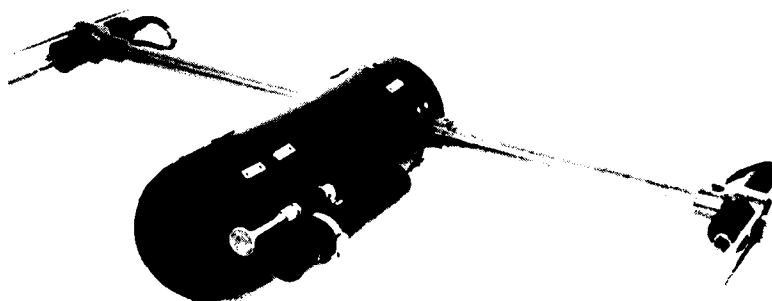
The thermistor of the Wien bridge oscillator is made by VECO (type Z32A91) and constitutes the resistive element in an oscillator designed at the Laboratory. The WBO's are calibrated in the Laboratory facility; their resolution is 0.0004°C at 1°C and their accuracy is about 0.01°C . The WBO can detect very minute, localized changes in water temperature because the thermistor's time constant is quite short (80 to 100



a. "Standard" nose package



b. Triple temperature probe



c. Fluorometer with temperature probes

Figure 8. Instrument Probes

msec). Figure 8b shows a triple-WBO instrument probe used to study ocean microstructure on several recent cruises. With this probe the vehicle is usually run along shallow-angle dive and climb trajectories.

Recently the WBO has been applied to conductivity measurements wherein the resistance of the water in a conductivity cell becomes the frequency determining element. This technique has proved to be successful. The resolution is 0.6 $\mu\text{mho/cm}$.

Another, more recent, probe configuration (Figure 8c) contains a fluorometer developed at the Laboratory for detecting minute quantities of certain fluorescent dyes in water. The dyed water flows through the instrument's test cell where it is illuminated with light capable of exciting the fluorescence. The scattered fluorescent light is filtered out and focused onto a photomultiplier tube. The resulting current from the tube is amplified and converted to a frequency. The instrument can measure Rhodamine B dye concentrations ranging from 10^{-12} to 10^{-6} g/cm³. It uses four overlapping ranges to cover this dynamic range. The fluorometers have been used successfully in three experiments: two diffusion experiments in the Pacific and a study in Puget Sound to measure tidal flushing of a bay for a proposed nuclear power plant. See Reference 10.

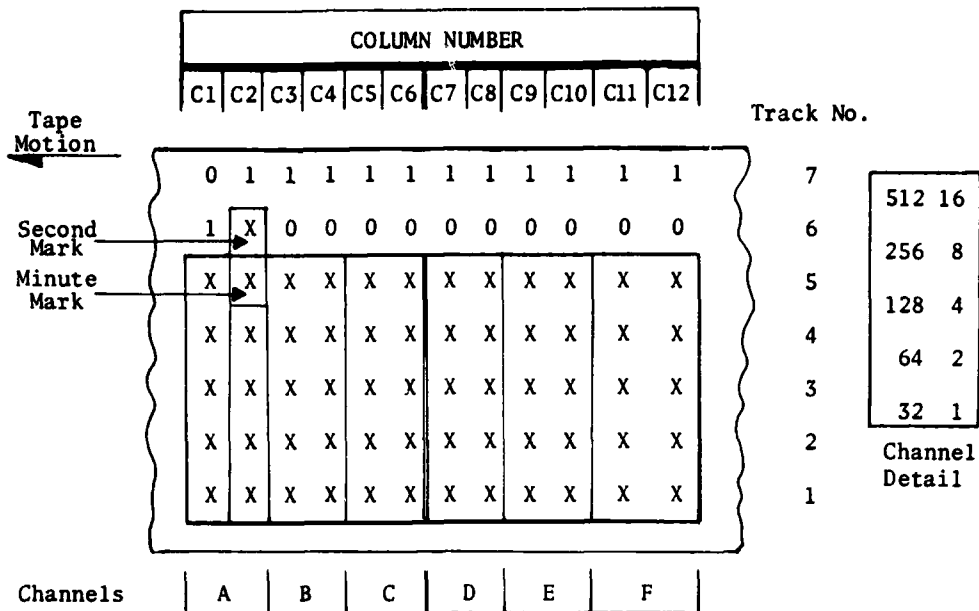
DATA SYSTEM

All data are recorded internally on magnetic tape; some oceanographic and vehicle operation data can also be telemetered to the ship acoustically. The data system is described in detail in Reference 2 and will be only summarized here.

The data are converted to binary form and are sampled periodically. The more important data are sampled 12 times a second and most of the oceanographic data are recorded at this rate. Vehicle data are sampled at rates varying from 12 times a second to once a second.

Figure 9 on page 22 shows the most recent data arrangement and also where the bits are physically located along the tape. The figure shows 1/12th second (about 0.06 inch) of the tape, which contains a single tape "word." The word is divided into six data channels, each using two columns of bits. The weighting of the 10 data bits is also shown in the figures; the more significant bits are placed in the first column of a channel. Channels A, B and D are SPURV functions, some of which are sub-commutated. The remaining channels are used interchangeably for the various oceanographic data listed.

There are several ways to display the data for study and analysis. In the older method the tapes are read directly into a photo-sensitive paper strip recorder. Vehicle tapes are also transferred to



Ch.	Word	Bit	Data	Ch.	Word	Bit	Data
A	all	1	Right Rudder	B	8	"	Receiver AGC Level
	"	2	Left Rudder		11	64	1 Command Bit
	"	4	Up Elevator			128	2 " "
	"	8	Down Elevator			256	4 " "
	"	16	Minute Mark			512	8 " "
	"	32	(Speed Ind. 1)÷4	12	all	Depth Step Register	
	"	64	(Speed Ind. 2)÷4	C	all	1 to 128	Fluorometer Freq. (VCO÷2)
	"	128	(Motor rpm)÷2		"	256, 512	Fluorometer Range " "
"	256						
"	512						
B	1	all	slow WBO (once every 2 seconds)	E	all	all	Sound Velocity/Conductivity
	2	"	} Pitch	F	all	all	Temperature/Conductivity
	6	"					
	10	"					
	3	"	} Roll				
	9	"					
	4	"					
	5	"	Turn Step Register				
7	"	Motor Current					

Figure 9. Data tape format and content

computer-compatible tapes, after which the data can be printed out or plotted using the IBM 1130 computer and its peripherals. A recently developed program provides a printout of all key data, averaged over intervals of 80 seconds of the run, which can be available about one-half hour after vehicle recovery and provides a very rapid check on system performance.

TAPE RECORDER

The tape transport for internal data storage was developed at the Laboratory specifically for SPURV. It is mounted on the forward end of the data chassis (see Figure 2); its dimensions are 12 x 7 x 3.6 inches and it weighs 6.1 pounds; its power requirement is 9 watts. The tape is one-half inch wide, the recording density is 200 bits/inch, and there are 7 tracks. The custom tape reels hold 1450 feet of one-half mil thick tape, enough for 6.5 hours of data. Mechanical tape drive is accomplished by a capstan and pinch roller which pull the tape past the record head. A miniature 400-Hz, 12,000-rpm hysteresis-synchronous electric motor coupled to the capstan through a precision gear train and flat belt provides the drive power and accurate speed.

Tape tension is maintained by an O-ring belt drive and friction clutch between the two tape reels; the belt drive ratio is such that the take-up reel is driven faster than the supply reel. Since the tape will not allow this to happen, slip must occur in the clutch. The slip torque of the clutch, combined with the effective radius of the supply reel, determines the tape tension (2.0 ± 0.5 oz) at the head. The system allows the tape tension to increase approximately 50% during the recording cycle.

Tape rewind is accomplished by manually releasing the capstan pinch roller, which at the same time reverses the drive motor's rotation. The reverse gear train rotation engages a one-way clutch which directly drives the rewind take-up reel. Tape tension arrangement is maintained by another belt drive and slip clutch as during record. The belt drives of the tensioning systems are automatically engaged and disengaged by one-way clutches so that no solenoid power is required. Since no solenoids are used in the transport the spring-loaded capstan pinch roller must be manually released when not in service to prevent flats from forming on the neoprene roller. Release is accomplished by turning the mechanical switch on the head plate to RW.

LAUNCH AND RECOVERY

Vehicle handling methods, particularly for recovery, have evolved perhaps more than any other feature. Methods have ranged from using the ship's boom for launch with swimmers going into the water to tie on recovery lines, to the small boat and portable hydraulic crane

we are using at present. These two tools--the modern stable inflatable boat and the small but powerful articulating crane--have vastly reduced handling problems. The crane, manufactured by Ramey, is bolted and welded to the ship's railing and deck and is operated by Laboratory personnel. Its booms have a reach of 16 feet from the side of the ship, its whip is 30 feet long and its capacity is 2000 pounds at full reach.

Figure 10 shows some launch and recovery operations from recent cruises. For launch the vehicle is held a few feet above the surface by a launch bar which is tripped with a line from the deck. The vehicle is dropped with the ship underway at about 2 knots. On the vehicle's return to the surface the ship is maneuvered to within about 100 meters and the crane is used to launch the boat; the crew attaches the recovery bridle, tows the vehicle into range and attaches the crane's whip. With the boom fully extended the whip is used to pull the vehicle toward the ship with the boat crew stabilizing the operation. When the vehicle is close enough and the waves are favorable, the boom is quickly raised clear of the water. Further tightening of the whip snubs the bridle on the end of the boom and prevents swaying. After the vehicle is swung aboard and laid in its cradle the boat and crew are brought aboard. The whole operation takes from 15 to 30 minutes, depending upon how close to the ship the vehicle is brought up, and can be done safely in sea states up to 6 and winds up to 30 knots, which about corresponds to the limit of acceptable working conditions on the smaller AGOR ships that are the usual operating base.

FUTURE DEVELOPMENT

An improvement which has already been implemented is use of the higher capacity LR-130 silver-zinc cell. The cell is only slightly larger than the LR-90 but has 20% more plate area. One battery box has been widened to accept these cells and they were used extensively on the latest cruise. Run times of 6.5 hours should be routinely attainable with these cells.

A battery charging system to permit automatic full charging of each cell is being designed. This system will bypass cells individually as they reach full charge and should reduce the labor attendant to battery charging and improve safety. In addition, about 3 to 4% more energy storage may be realizable. The use of ac or pulsed charging has been said in recent literature to yield up to 30% gains in energy storage--this change would cost very little.

Changes in the propulsion system which appear worthwhile are a permanent magnet motor and a new or modified propeller. A permanent magnet motor would save the 7.5% of total current now used for field current. Our present propeller is pitched for 6 knots and does not work at peak

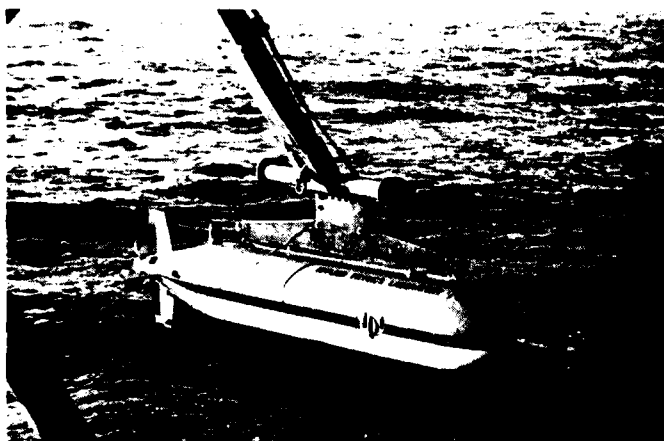


Figure 10a. Vehicle on launch bar ready for release.

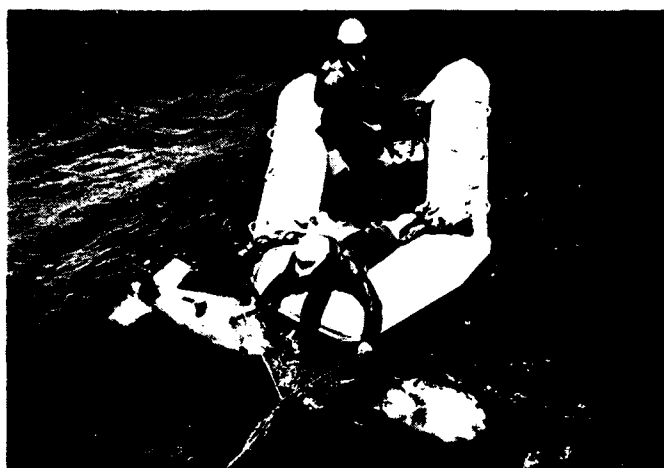


Figure 10b. Recovery team attaches bridle and steadies vehicle as whip is pulled in.

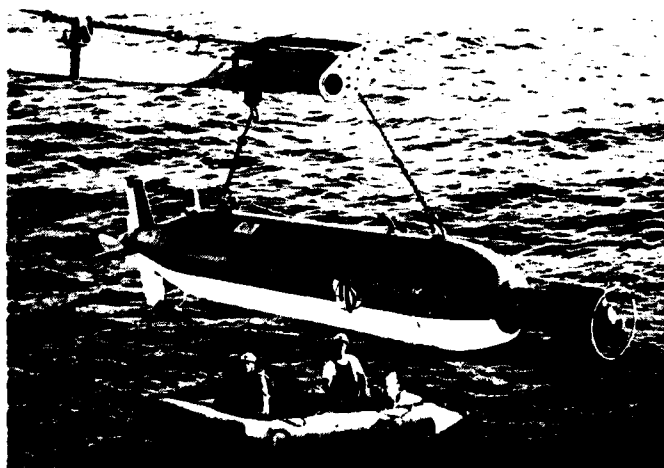


Figure 10c. Vehicle clear of water and snubbed in tight.

efficiency at 4 knots. Some simple drag reduction effort might also increase the speed and bring the propeller into a more favorable operating range.

Even with only the battery cell change the improved vehicle endurance will require that the tape recorder and the run timer be modified. Both devices can readily be slowed down. A 50% increase in tape capacity should be easy to achieve. The greater bit density on the tape has been found acceptable.

Improvements in performance could be realized by a change to a linear depth control system. A new reference using a quartz crystal pressure sensor to replace the Vibrotron would increase long term accuracy. The quartz devices are about an order of magnitude more stable and are more widely manufactured.

The vehicle's transponder transmitter will be modified for greater output power and greater tolerance margin.

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APPENDIX A

DEPTH OPTIONS

The depth step and depth ramp systems are shown as a single block in Figure 5 and their operation is briefly outlined in the depth system discussion. The block diagram of Figure A1 shows the two systems in greater detail. Both figures shown common ingredients: a frequency divider, control flip-flop, and gating. These circuits use the same cards, which, coupled with the sharing of commands 5 and 6, explains why only one mode can be used during a vehicle run. The step values are, of course, similar (2, 4, 8, 16, 32, 64 or 128 bits per step) and are set by wiring on the instrumentation chassis. The resulting depth change per step can vary from 0.06 meter to 3.8 meters. Both modes are enabled only after the vehicle is within 30 meters of the preset depth, i.e., when the coarse depth error goes to zero.

Depth Step Mode

Since the depth step system counters are 8-bit elements with each bit equaling one step, the range of the system is 256 steps. During a run the counter should not be driven more than 128 steps above or 127 steps below its starting position. If too many steps are commanded the counter will "wrap around" and what was planned as a dive will be a climb. Steps stored in the counter will affect all three operating depths. There is no reset feature--steps in one direction can only be canceled out by sending steps in the other direction. The depth steps are loaded in parallel into the step command register, which is a down counter. The start pulse clocks the counter to zero and produces the step pulse.

Depth Ramp Mode

The depth ramp mode is quite similar to the step mode, the essential difference being 12-bit rather than 8-bit range. With 12-bit counters the count can go as high as 4096. At the current rate of 1 step per second the ramp can last for 68.27 minutes. The ramp must start with a dive command of any number of steps and a hold must be sent to stop the ramp whether temporarily or permanently. To reverse direction, a hold command must be sent before a climb command because the flip-flops are interlocked. The duration of the climb must be less than the dive to prevent counter wrap-around. The program may be terminated at any point by sending a reset command, which clears the counter and flip-flops and brings the vehicle up at the maximum pitch of 45° to the starting depth.

The timing diagram illustrates the sequence of events for the depth counter system. It shows the relationship between various inputs and the state of the counters and control logic over time.

- Inputs:**
 - 5.69 MHz FROM OSCILLATOR:** Provides the base frequency to the Frequency Divider.
 - DEPTH ENABLE:** A control signal that enables the depth counter.
 - START PULSE 12/SEC:** A periodic pulse that triggers the Control Flip-Flop.
 - 1 STEP/SEC:** A periodic pulse that provides the step rate for the up/down counter.
 - COMMAND 6 AND DIVE STEP:** A combined signal that triggers the DIVE counter.
 - COMMAND 5 AND CLIMB STEP:** A combined signal that triggers the CLIMB counter.
 - COMMAND 14 RESET:** A signal that resets the up/down counter.
 - COMMAND 13 HOLD:** A signal that holds the up/down counter.
- Logic and Counters:**
 - FREQUENCY DIVIDER:** Divides the 5.69 MHz signal by a factor of 2 to 128. Its output is wired to the CLK input of the 12-BIT DELAY COUNTER.
 - CONTROL FLIP-FLOP:** Receives the START PULSE 12/SEC at its S input and the output of the 12-BIT DELAY COUNTER at its R input. Its output is the DELAYED START TO DEPTH COUNTER.
 - 12-BIT DELAY COUNTER:** Counts down from 12 bits, providing a 12-bit output to the COMPARATOR.
 - COMPARATOR:** Compares the 12-bit output of the delay counter with a reference value. Its output is the DELAYED START TO DEPTH COUNTER.
 - UP 12-BIT UP/DOWN COUNTER:** Counts up or down based on the 1 STEP/SEC input and the output of the COMPARATOR. It has a CLEAR input and outputs for COMMAND 14 RESET and COMMAND 13 HOLD.
 - DIVE and CLIMB Counters:** Two 12-bit counters that count down from 12 bits. The DIVE counter is triggered by COMMAND 6 AND DIVE STEP, and the CLIMB counter is triggered by COMMAND 5 AND CLIMB STEP. Both have Q and D outputs.

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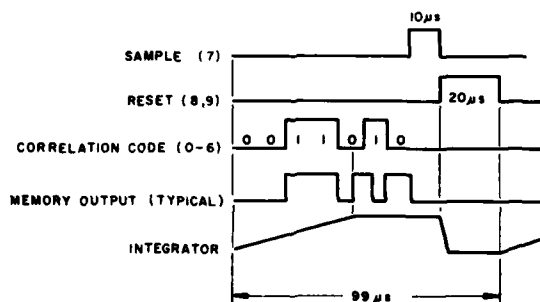
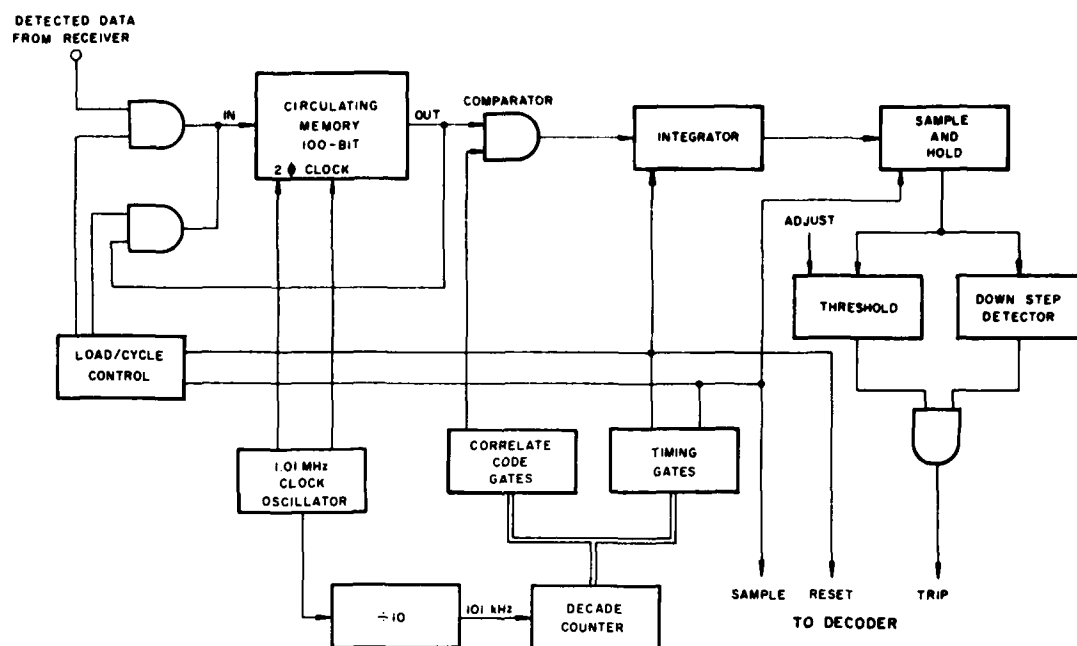


Figure A2. Correlator block and partial timing diagrams

CORRELATOR

The correlator is an application of the principles of the Deltic Correlator described in Reference 9. Figure A2 is a block diagram of the correlator portion of the decoder. A similar system is used in the tracking receivers on the mother ship.

The correlator continuously receives detected data from the receiver and stores samples from the data in a 100-bit, MOS dynamic memory. The bits in the memory are shifted at a 1.01 Mhz rate; hence a complete memory cycle occurs every 99 μ sec. Once in every memory cycle a new bit is loaded and an old bit is discarded; hence the memory is updated at a rate 1/100th of its clock rate, or 10.1 kHz. Since the single bit of normal incoming data lasts 1 millisecond, the memory takes 10 samples from each data bit. The correlation code consists of 7 bits (coded 0011010) so a total of 70 samples is sufficient to store the entire code. Note that this process essentially speeds up the received data by a factor of 100.

While the incoming data are being sampled, stored and circulated, a replica of the correlation code is generated in synchronism by decoding the decade counter. The generated code is compared with the speeded-up received data and during the times when the two are identical an integrating capacitor is charged from a constant current source. The capacitor voltage is therefore proportional to the correlation observed between the two signals during a given memory cycle.

The waveforms in Figure A2 illustrate the timing of one memory cycle. The counts of the decade counter used to generate the various signals are also listed. The memory output is shown as it might appear if about the first 4-1/2 bits of the correlation code had been correctly loaded. The integrator charge builds up only during the period of equality and the peak level attained is stored on the sample pulse. After the sample the integrator is reset to zero.

If the correlation is improving, the level of the steps in the sample and hold circuit becomes higher and passes the maximum. On the first downward step above the required threshold the trip pulse is generated. Perfect correlation would be 70 out of 70 correct matches but this precision is not required. The threshold is set at a level of 62 of the possible 70. Note that the master oscillator frequency is slightly higher than a decade multiple of the incoming data rate. This assures that the 70 samples are taken and the correlation trip occurs slightly before the end of the correlation code and well before the first command bit must be loaded.

The main purpose of the correlator is to synchronize the loading and averaging of the remainder of the word to the vehicle; it cannot prevent occasional false data bits. False data are prevented from affecting the vehicle by the averaging, redundancy and parity requirements.

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<p>The Self-Propelled Underwater Research Vehicle (SPURV) has been under development at the Applied Physics Laboratory for over ten years and is a reliable and practical research tool. Instrumentation developed for SPURV includes temperature and conductivity probes, a fluorometer for dye tracing experiments and a data recording system. Oceanographic and vehicle performance data are multiplexed and digitized and taped on a special recorder, Digital-computer data reduction provides a run summary printout and system performance check a short time after a run. Data are also telemetered acoustically to the mother ship which carries a transducer array for receiving data and tracking and commanding SPURV. Frequency-shifted and digitally-coded signals are used for the acoustic link. A special code, detected by correlation techniques, is used to enhance data accuracy. SPURV's depth control uses a digital reference which is manipulated to provide incremental, sawtooth or long, slow, ramp-like depth excursions. Course changes and an azimuth program are also available on command. SPURV has been operated on over 100 runs at sea, mainly from Navy AGOR-type ships. Launch and recovery tools and techniques have been steadily refined and can cope with any reasonable sea state.</p>			

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